

Mimas: Tectonic Structure and Geologic History.

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Introduction. Mimas, the innermost of the major saturnian satellites, occupies an important place in comparative studies of icy satellites. It is the smallest icy satellite (mean radius = 199 km) known to have an essentially spherical shape (Thomas et al., 1986). Smaller icy objects like Hyperion and Puck are generally irregular in shape, while larger ones like Miranda and Enceladus are spherical. Only Proteus, a newly discovered satellite of Neptune (1989N1, see Smith et al., 1989), is slightly larger than Mimas and yet has a significantly non-spherical shape. Thus Mimas is near the diameter where the combination of increasing surface gravity and internal heating begin to have a significant effect on global structure. The nature and extent of endogenic surface features provide important constraints on the interior structure and history of this transitional body.

The major landforms on Mimas are impact craters. Mimas has one of the most heavily cratered surfaces in the Solar System (Plescia & Boyce, 1982; Strom, 1987; Lissauer et al., 1988). The most prominent single feature on Mimas is Herschel, an unrelaxed complex crater 130 kilometers in diameter. Relative to the radius of the satellites, Herschel is one of the largest craters in the solar system. The craters themselves are unremarkable, with morphologies and dimensions comparable to craters on other icy satellites (Schenk, 1989).

The only other recognized landforms on Mimas are tectonic grooves and lineaments. These structures were briefly described by Smith et al. (1981). Groove locations were mapped by Schenk (1985, 1989) in a search for directional trends that could related to recognizable stress sources, but without analysis of groove structures or superposition relationships. Mimas' tectonic structures are re-mapped here (Figure 1) in more detail than previously as part of a general study of tectonic features on icy satellites.

Description. Mimas' tectonic features have been divided into three major classes on the basis of width, morphology and relative age. Subclasses are defined on the basis of orientation.

Class 1: Fresh Chasmata. Only two features are included in this class, Ossa and Pelion Chasmata. Although they are not the largest tectonic features, they are the most prominent. These chasmata are V-shaped troughs typically 10 km wide, 2 - 3 km deep, and in segments 100 to 150 km long. The depths are based on photoclinometric profiles (Schenk, 1989), limb profiles (Dermott & Thomas, 1988), and stereo comparison with nearby fresh craters. The chasmata form a single system oriented roughly east-west between 20° and 30° south latitude. A circle fit to the chasmata segments by least-squares has a center at 57.5° N, 258° W and an angular diameter of 172°, very nearly a great circle. These features formed relatively late in Mimas' geologic history: they are superposed by several fresh craters, but cut through older, more degraded craters.

Class 2: lineaments. This class comprises a large number of long, narrow features. Lineament widths range from near the limit of resolution (1-2 km on the best images) to about 4 km. Lineament segments range in length from a few tens to several hundreds of kilometers. Vertical topographies are estimated to be on the order of hundreds of meters. Lineaments exhibit a variety of morphologies: a) scarps or ridges, good examples are located tangent to the crater Gawain in FDS #s 34938.18, 34940.34; b) graben-like grooves, good examples between the crater Arthur and Pelion chasma and just south of the craters Uther and Igraine; and c) and at least one chain of pits running north-south between 30° and 60° south near 350° west.

Most of the lineaments are members of curvilinear sets of parallel structures with fairly constant spacings and distinct orientations. Five sets are defined in Table 1, labeled by nearby features for convenience. There are also a few individual lineaments which cross the labeled sets at significant angles: one centered near 40° S, 340° W crossing set 1 at an angle near 60°, another near 40° S, 290° W crossing set 2 at near 60° (both seen in FDS #34944.21), and a poorly defined feature near 30° N, 195° W crossing set 4 at nearly right angles (best seen in FDS #34938.18). The first two individual lineaments cross Pangea Chasma and are roughly parallel to each other. There are a number of other possible lineament segments between these two lineaments visible in FDS #34944.21 that appear to follow the same directional trend. These features may comprise another lineament set ("Trans-Pangea"), but if so, they are very poorly defined. Sets 1 & 3 are topographically prominent compared to sets 2 & 4, probably in part because sets 2 & 4 are imaged at significantly higher sun angles than sets 1 & 3. Set 5 is also topographically prominent, but less well characterized because of the significantly lower resolutions (4-6 km/pixel) at which it was imaged. Most of the lineament sets may be parts of a single global system: extrapolation of the gently curving trend of set 2 connects smoothly onto the trends of set 3; set 1 trends change smoothly in a counter-clockwise sense from W to E, becoming close to the trends of set 3 near the common boundary of both sets; certainly the trends of both sets 1 & 3 become nearly parallel in the south polar area and connect directly onto the trends of set 5. It must be noted that though the trends may be concordant between sets, lineaments directly connecting the sets, particularly over the south pole area, have not been found, perhaps due to the limited imagery.

Superposition relations indicate that most of the lineaments formed relatively late in Mimas' geologic history. Like the fresh chasmata, the lineaments in the sets cross some impact craters and are cut by others. Straight sections of the rims of some fresh craters (e.g., SW rim of Igraine) also indicate the establishment of the structural pattern before the formation of many of the fresh craters. Set 5 crosses Herschel, indicating structural activity after Herschel's formation. Superposition relations between the lineament sets and the fresh chasmata are uncertain. Ossa Chasma cuts across the trends of several lineaments in set 2. No continuation of lineament structure can be seen across Ossa's floor (see FDS #34940.34) and a lineament may form a "T"-type termination (see Golombek & Allison, 1981) at Ossa's eastern end, suggesting a later formation for the chasma. However, the resolution of available images is too poor to be sure. The "trans-Pangea" and the other individual lineament are heavily degraded and are very difficult to trace at times, suggesting that they are substantially older than the lineament sets.

Class 3: Degraded Chasmata. The largest tectonic features on Mimas are the degraded chasmata and scarps. This group of features includes the other named chasmata (Oeta, Avalon, Tintagil, Pangea, and Camelot), and a few large, apparently unpaired scarps. These scarps, previously undocumented, occur between the craters Herschel and Morgan, and define three large horst-like blocks centered near: 1) 15° S, 150° W (seen in FDS #34933.50, 34936.23, and 34938.18 on the terminator), 2) 40° N, 157° W (FDS #34933.50 and 34936.23), and 3) 15° N, 182° W (FDS #34936.23 and 34938.18). The eastern sides of the blocks parallel the Avalon and Oeta chasmata, whereas the western sides of the latter two blocks are more north-south. The chasmata are typically 15-20 km wide and a few kilometers deep. Most of the degraded chasmata appear to form a single globe-girdling set of features reminiscent of the Ithaca Chasma system of chasmata on Tethys: Avalon, Oeta, Tintagil, and Pangea chasmata all fall within a few degrees of a great circle with a pole near 30° S, 67° W, and define about 212° of its circumference. Camelot Chasma and its branch past Iseult crater angle about 30° counter-clockwise away from the "great circle" system, thus bearing about the same relation to it as the Polar-Odysseus Tangent chasmata on Tethys bear to the Ithaca system (Croft, 1991).

As implied by the class designation, all of these features are heavily degraded by superposed impact craters. Their heavily cratered state indicates that they are older than most of the lineaments, and the "trans-Pangea" group lineaments cross Pangea Chasma. Two lines of evidence suggest that these chasmata predate Herschel. First, the scarps and chasmata appear more heavily cratered than Herschel, and many of the superposing craters are muted in appearance, suggesting that they are overlain by Herschel ejecta (Schenk,

1989). Second, Oeta Chasma is directly superposed by Herschel. Pangea and Camelot Chasmata cannot be directly related to Herschel stratigraphically. If Pangea Chasma is part of the same system as Avalon, etc., then it may have formed at the same time (prior to Herschel). However, just as the Ithaca system has segments of different ages, Pangea may not have formed at the same time as Avalon/Tintagil. Camelot is placed in the same group because of its heavily cratered appearance.

Other Features. A search was made for other geologic features that might not be due to impact or tectonic processes. None were noted except a horseshoe-shaped dark patch about 50 km wide and 70 km long near 20° S, 357° W visible in the last and highest resolution sequence of images of Mimas (FDS #34944.17 ff). The patch is about 20% darker than its surroundings, but does not stand out on the color ratio map of Buratti et al. (1990). The patch does not appear to be due to partial shadowing; although part of it lies in a shallow trough, it also extends over the rolling cratered terrain; further, the patch makes a continuous 180° turn without an obvious break or change in apparent albedo, difficult to achieve by topographic alone. The edges of the patch are moderately sharp. The patch appears to be dark material draped over the topography of the heavily cratered surface with no apparent thickness. The arms of the horseshoe extend along lines parallel to nearby Pangea Chasmata. No similar feature was seen elsewhere on Mimas.

Discussion. The range in preservation states of Mimas' tectonic features, and superposition relations between them and the craters indicate that tectonic activity continued over a period of time comparable to that required to form the suite of visible craters. The degraded chasmata formed first, followed by the Herschel impact, and then the lineaments and the fresh chasmata. If this order is correct, it implies that most of the tectonic strain was generated before the Herschel impact.

The number and locations of tectonic features found here largely agree with those mapped by Schenk (1989). He proposed that the grooves may be related to the formation of Herschel, but that groove orientations may also permit a tidal origin as well. Schenk grouped all of the mapped features together in his stress trajectory analyses. However, as noted here, the tectonic features can be divided into classes with different morphologies, orientations and formation times, suggesting that more than one stress source may need to be invoked to account for them.

The axis of the fresh chasmata system is approximately radial to the crater Herschel: a great circle fit to the segments is tangent to Herschel's NNW rim. Schenk (1989) suggested that this geometry indicated that these chasmata may be due to fracturing by the Herschel impact, perhaps analogous to the grooves on Phobos around the crater Stickney (Thomas, 1979). This is certainly possible as there are some similarities. However, the chasmata are in the hemisphere antipodal to Herschel and no fresh chasmata occur closer than about 90° from the crater, whereas the most prominent grooves on Phobos cluster on Stickney's rim. The lineaments that do cross Herschel appear not to be related to fresh chasmata system.

Lineament set trends can be fit into at least two possible global frameworks. First, sets 1, 2, 3, and 5 can be interpreted as parts of a roughly concentric set of lineaments centered near 20° N, 190° W. The "center" is poorly determined due to the broad width of the sets and the lack of images that could constrain the extent and trends of the assumed system into the northern hemisphere. Such a concentric system could be related to cyclic tidal deformation resulting from high orbital eccentricity (Helfenstein & Parmentier, 1980), but relative to a different long axis than the current one. Set 4 does not seem to fit this putative global concentric pattern, as its trends are at roughly right angles to its eastern neighbor, set 5. Thus set 4 and the individual lineaments would need to have been formed by a different set of stresses than sets 1, 2, 3, and 5. Second, all of the lineament sets may be parts of a global set of conjugate fractures running around Mimas' equator. If the "trans-Pangea" set is real, the cross pattern between them and set 1 would be an example of a conjugate set. Such a system could be due to tidal despinning superposed on global expansion (Melosh, 1977). However, no circumpolar normal faults also predicted by the despinning model are apparent. Further, lineament cross-patterns are not apparent in the other images, only single trends. Finally, the broadly curved traces of the lineaments and the change in trends within and between sets (e.g., set 1) do not appear to follow a simple conjugate fracture pattern.

The origin of the degraded chasmata system might be attributed to the formation of Herschel analogous to Odysseus and Ithaca on Tethys. However, in this case, the pole of the great circle is a crater radius outside Herschel's rim, and the chasmata are apparently older than the crater, indicating that the degraded chasmata are unrelated to the giant impact. The origin of the system is unclear. It may be related to internal convection patterns.

Based on morphology, the tectonic features on Mimas are all interpreted as extensional in origin. No compressional features appear to be present. The areal extension represented by the classes of tectonic features can be estimated using the method of Golombek (1982), in which the new area (A) for each scarp is related to the length (L), depth (d), and assumed angle of dip (Θ) for the underlying faults by: $A = Ld/\tan(\Theta)$. Adopting $\Theta = 60^\circ$ and noting that features like the chasmata have 2 scarps (twice the area of a single scarp) yields the following areal increases from the cumulative measured lengths of the three tectonic groups: 1) fresh chasmata (adopted $d = 3$ km) - 0.4%, 2) lineaments ($d = 0.3$ km) - 0.2%, and 3) degraded chasmata ($d = 2$ km) - 1.2%. Given the obvious uncertainty in the adopted depths, these estimates are probably only good to within a factor of 2. However, these results: 1) indicate the relative tectonic importance of the different classes of features, 2) are similar to the expansion estimates obtained for the uranian satellites (Croft & Soderblom, 1990). Neither the inferred areal expansion nor the implied failure stresses (10-20 bars) can be obtained from traditional thermal models for Mimas (e.g., Ellsworth & Schubert, 1983). However, preliminary calculations indicate that both the expansion and necessary stress levels can be reached for Mimas if a deep, low conductivity regolith is assumed.

The question of cryovolcanic activity on Mimas is unresolved. Plescia & Boyce (1982) resurfacing in the south polar area on the basis of a local paucity of large craters. Lissauer et al. (1988), however, suggest that the lack of large craters in the area is consistent with random statistical variations, and thus does not constitute evidence for resurfacing. There are no apparent extrusive features on Mimas, unless the dark albedo spot is one. The characteristics of the patch may be accounted for by low-energy extrusion or expulsion along pre-existing fractures, somewhat like the swirls on Dione and Rhea. Its orientation along trends parallel to nearby chasmata is consistent with this model. However, the feature also resembles dark deposits around impact craters on other icy satellites unrelated to extrusive processes.

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Table 1. Lineament Set Parameters

Set Designation	Center	Spacing	Direction Trends	Best Image
1. Pangea-South Pole	55° S, 340° W	15-20 km	N-S to 20° west of north	34944.21
2. Trans-Ossa	20° S, 280° W	6-10 km	10° to 30° west of north	34940.34
3. Uther-Gawain	55° S, 250° W	≈20 km	NW-SE	34938.18
4. Morgan-Modred	20° N, 200° W	≈10 km	30° west of north	34938.18
5. Herschel-Galahad	30° S, 130° W	15-30 km	NE-SW	34932.04, 20

Figure 1. Geologic sketch map of Mimas. Base is USGS Map I 1489.

